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Municipal Sludge Composting Technology Evaluation

Brown and Caldwell, Pleasant Hill, CA

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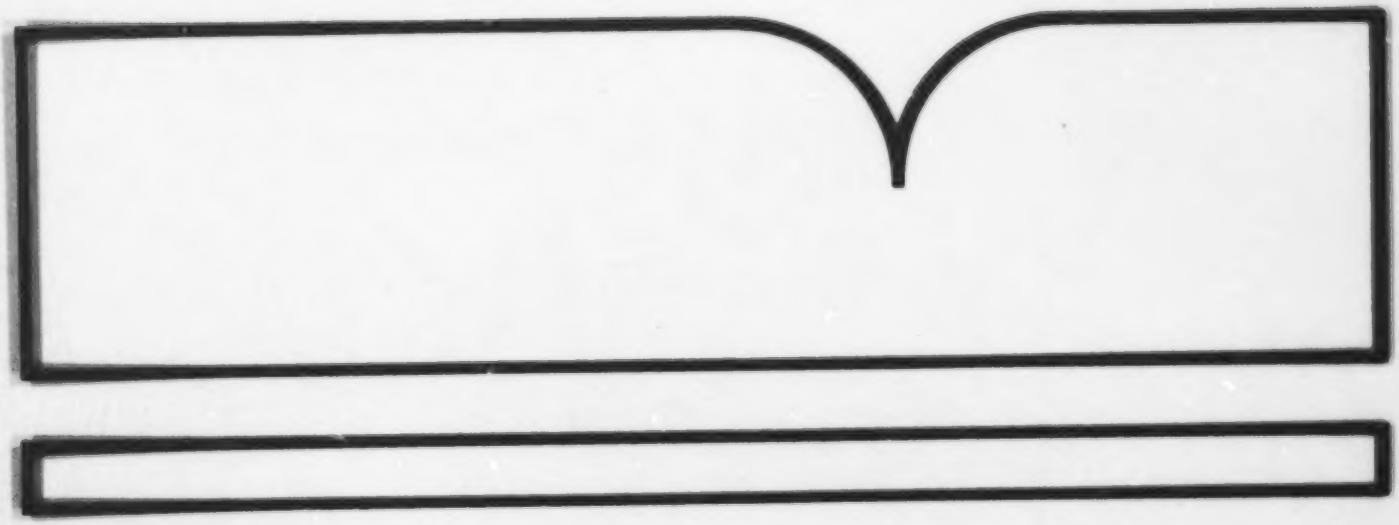

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16. ABSTRACT

This paper summarizes the findings of a technology evaluation of municipal sludge composting as demonstrated at five facilities: three with aerated static piles, a windrow, and an aerated windrow. Although all of the sites generally processed sludge reliably and effectively, the intent of this paper is to present key problem areas and their resolutions. The evaluation relied on short site visits and review of readily available records.

Site and operating features, sludge loadings, compost characteristics, capital and operation and maintenance (O&M) costs, compost revenues, and procedures to minimize odors are presented. Several general conclusions were reached:

- Moisture control (total solids $\geq$ 40%), efficient mixing, and flexibility of operations were all important for proper composting.
- Wood chip recoveries were typically only 65 to 85 percent.
- Finished compost production was affected by the type of sludge processed, but not the composting technology, and ranged from 0.6 to 2.2 dry Mg per dry Mg of sludge.
- Odor was the chief environmental problem at the facilities.
- For static pile facilities, O&M costs were site specific and ranged from $28 to $40 per wet Mg of sludge (windrow unit O&M costs were not available).
- Revenues varied from $0.65 to $2.75 per wet Mg of sludge.

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FOCUS

Municipal sludge composting technology evaluation

Arthur H. Benedict, Eliot Epstein, John N. English

Widespread interest in composting as a means of municipal sludge treatment began in the early 1970s, and has increased dramatically since that time. In 1984, the U. S. Environmental Protection Agency (EPA) initiated a technology evaluation of municipal sludge composting based on investigations at five operating facilities.[1] The facilities studied generally processed sludge reliably and effectively; however, this paper presents key problems experienced and their resolutions. Varied features of the composting technologies are also compared.

COMPOSTING TECHNOLOGIES

The municipal sludge composting technology evaluation focused on three composting processes: the extended aerated static pile process, the conventional windrow process, and the aerated windrow process. Schematics for the three processes studied are presented in Figures 1, 2, and 3.[2-4]

The aerated static pile process involves mixing dewatered sludge with a bulking agent, such as wood chips, followed by active composting in specially constructed piles (Figure 4). Induced aeration is provided during active composting and sometimes during curing or drying. The active composting period lasts at least 21 days, after which alternate pathways to produce finished compost may be used, as shown in Figures 1, 2, and 3.

The conventional windrow process involves mixing dewatered sludge with a bulking agent such as finished compost, often supplemented with an external amendment, followed by formation of long windrows (Figure 5). An active windrow composting period is 30 days or more, during which the windrows are turned periodically (typically two to three times per week) to aerate and remix the material. After the active windrow composting period, the composted material is allowed to cure for at least 30 days. A portion of the finished compost is then recycled and another portion is stockpiled for distribution. The aerated windrow process is similar to the conventional windrow process except that induced aeration to enhance active composting and drying is provided in addition to aeration by turning.

FACILITIES AND METHODS

This evaluation focused on operation, performance, and cost features at five facilities: the Hampton Roads Sanitation District Peninsula Composting Facility (Hampton Roads facility) in Newport News, Va.; the Washington Suburban Sanitary Commission Montgomery County Composting Facility (Site 2 facility) in Silver Spring, Md.; the City of Columbus, Ohio, Southwesterly Composting Facility (Columbus facility) in Franklin County, Ohio; the Joint Water Pollution Control Plant Composting Facility of the Los Angeles County Sanitation Districts (Los Angeles facility) in Carson, Calif.; and the Metropolitan Denver Sewage Disposal District Number One Demonstration Composting Facility (Denver facility) in Denver, Colo.

The scope of the evaluation varied at each composting facility. At three static pile facilities, investigators reviewed plant records and observed facility operations. Independent process testing was performed at the Hampton Roads and Columbus facilities, but not at the Site 2 facility. On-site studies at the Hampton Roads and Columbus facilities lasted 3 weeks each, whereas the on-site study at the Site 2 facility lasted for 4 days. The evaluation of conventional windrow composting at the Los Angeles facility was based on a 1-day site visit and a review of literature provided by facility personnel,[5-13] whereas the Denver aerated windrow facility evaluation was based on a 4-day site visit. No independent process testing was performed at either of the windrow facilities.

STATIC PILE OPERATION

Key features of the three static pile facilities investigated are summarized in Table 1. Operating areas, sludge loadings, and key composting operations at these facilities are assessed in the following sections.

Operating areas. The Hampton Roads, Site 2, and Columbus facilities use operating areas of 2.5, 16, and 15 ha, respectively. These areas are equivalent to unit operating areas of approximately 0.06, 0.04, and 0.08 ha/wet Mg · d, based on design sludge loadings of 45, 360, and 180 wet Mg/d. Operating area refers to the site area actually required for current composting operations, including access roads, buffer zones, support facilities, and storage ponds for runoff control, if required.

Three requirements for effective composting are integration with treatment plant operations, day-to-day control of moisture content, and flexibility to adapt to variable sludge loads.

Unit operating areas for static pile operations differ based on site-specific factors. For example, at the Hampton Roads facility drying is performed by spreading and rototilling unscreened compost on uncovered, concrete slabs; this process uses 140 m^2/wet Mg · d. In contrast, intensive aerated prescreen drying at the Site 2 facility uses only 9 m^2/wet Mg · d. In another example, about 4 ha are provided for unscreened compost storage at the Columbus facility because screening operations are affected by weather and because the market for finished compost distri-

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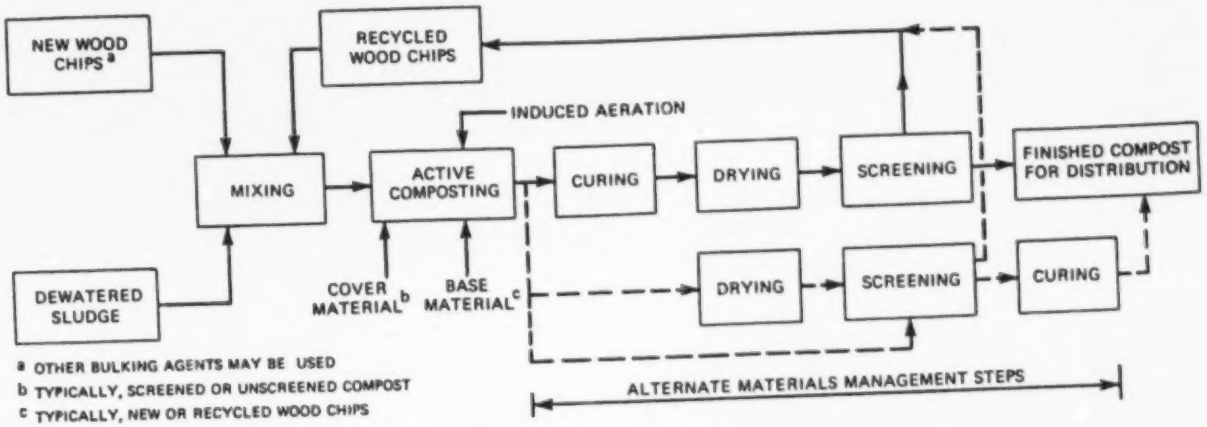

Figure 1—Aerated static pile process schematic.

bution is still being developed. This storage area is the main reason that the overall unit operating area is larger than the other static pile facilities investigated. Finally, while runoff containment ponds at the Site 2 facility require 102 m^2/wet Mg·d, the Columbus facility requires only 18 m^2/wet Mg·d. At the Hampton Roads facility, there are no runoff ponds.

Sludge loadings. Table 2 compares actual and design sludge loadings for each static pile facility investigated. The average total solids content of sludge received at each facility is below that estimated at design by 3 to 5%, and actual sludge loadings based on dry megagrams per operating day are between 70 and 110% of the design loadings. Actual loadings in the table are based on data from the evaluation and may vary from current loadings.

Bulking agent (wood chip) use is up to 80% greater than initial projections; lower-than-anticipated sludge total solids concentration accounts for this difference. Increased bulking agent use has affected materials flow and storage, equipment mobility, and operating costs. These problems have been resolved by the following: modifying on-site features and operation to increase materials management capabilities; purchasing additional materials handling equipment; investigating means of improving sludge dewatering; managing operation to maximize the use of recycled wood chips; and purchasing more wood chips.

Mixing. Dewatered sludge is mixed with recycled and new wood chips at typical (volume/volume) ratios of 3.5 to 4.5. The mix ratio varies with chip quality, sludge and chip moisture content, season, and the proportion of new and recycled chips used. All facilities use mobile mixing equipment (Table 1), and a minimum initial total solids concentration of 40% in the wood chip-sludge mixture is considered essential for effective static pile composting at all facilities.

Time-and-motion studies indicated that 40 to 45 minutes were required to achieve a well-mixed material with the sludge and wood chip quantities and mobile equipment used at the sites. As noted in Table 1, one facility coarse mixes with a front-end loader and then fine mixes with a manure spreader or rototiller. Fine mixing at another site is performed with three passes of a mobile composter. If only front-end loaders are used for mixing, the mix must be monitored carefully to ensure uniformity.

Static pile configurations. Pile construction and aeration features at each of the static pile facilities studied are summarized in Table 3. Perforated aeration piping is placed either directly on a paved compost pad, or in a trough cast into the pad. The piping is covered with base material, a sludge-wood chip mixture is placed on the base material in an extended pile configuration, and an insulating cover material is applied (Figure 4). Aeration piping is connected by a manifold to a blower that provides

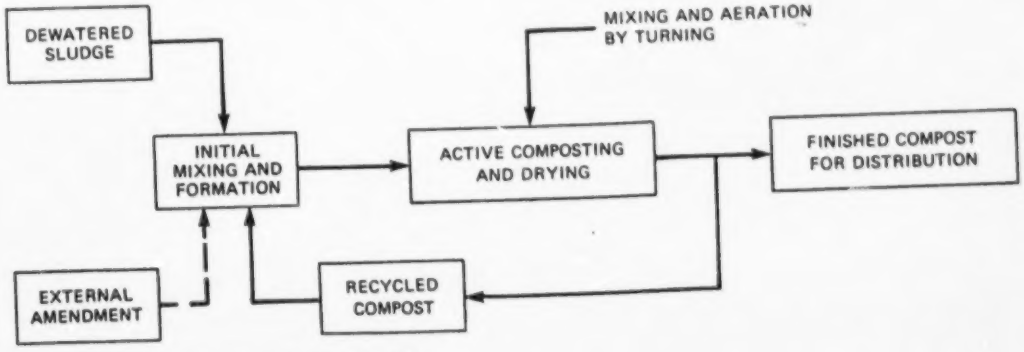

Figure 2—Conventional windrow process schematic.

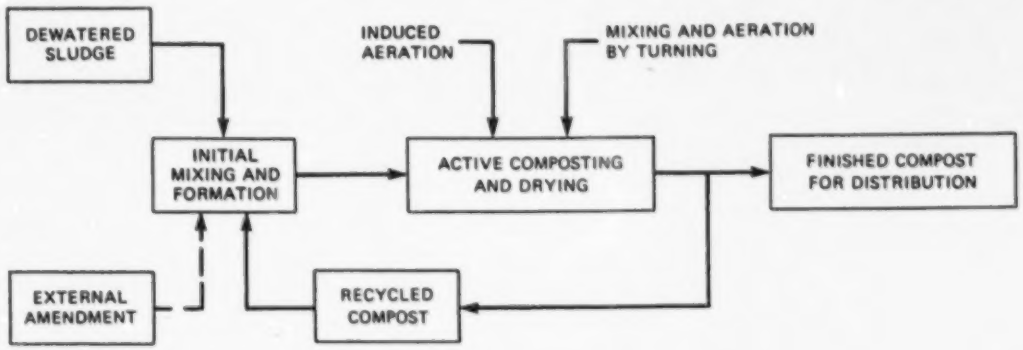

Figure 3—Aerated windrow process schematic.

either positive or negative aeration. Generally, one such extended pile compartment is constructed for each daily loading of dewatered sludge. Extensive testing after construction was required at the Hampton Roads and Site 2 facilities to achieve reliable pile construction and aeration techniques for routine operation, whereas conventional techniques were successful at the Columbus facility.

Process control. Aeration rates of 31 to 38 $m^3/h \cdot$ dry Mg are used at the Hampton Roads facility to maintain a residual oxygen of at least 5% and until a performance criterion of 55°C is reached for 3 consecutive days. Blowers are cycled 10 minutes on and 20 minutes off (with negative aeration in the winter and positive in the summer) to meet the 55°C performance criterion. High-rate, continuous, positive aeration at 78 to 87 $m^3/h \cdot$ dry Mg is used after the performance criterion has been achieved until the end of the 21-day active composting period.

The Site 2 facility aerates at 110 to 125 $m^3/h \cdot$ dry Mg during the first week of active composting. Aeration rate is then controlled to maintain temperatures of 50° to 60°C, including a minimum of 55°C for 3 days. After this, the rate is increased to 187 $m^3/h \cdot$ dry Mg until active composting is completed. Negative aeration is used throughout.

The Columbus facility uses manual blower control to aerate according to seasonal requirements. In winter, aeration is not started until the pile reaches 40°C; then blowers are cycled for 20 minutes on and 10 minutes off. In summer, aeration starts as the pile is constructed. Positive aeration is used and temperature monitoring is continued until three daily readings of 55°C or greater are recorded. After this, continuous aeration is maintained until the 21-day active composting period is complete.

Drying and curing. Typically, material composted by the aerated static pile method is not dry enough for efficient screening, and separate drying must be performed. At the Columbus facility, drying has continually caused problems and thus, as described previously, a large area (4 ha) for unscreened compost storage is used. At the Hampton Roads facility, unscreened compost is stored and cured until weather permits drying. Then it is spread out to a depth of 40 to 45 cm and rototilled to reach a minimum total solids content of 50%. This typically requires less than 3 days during the summertime when temperatures are high. After drying, material is piled under a covered shed until it is screened.

At the Site 2 facility, each pile is torn down by a front-end loader after the active compost period, and unscreened compost is transported to a covered drying area where it is restacked over

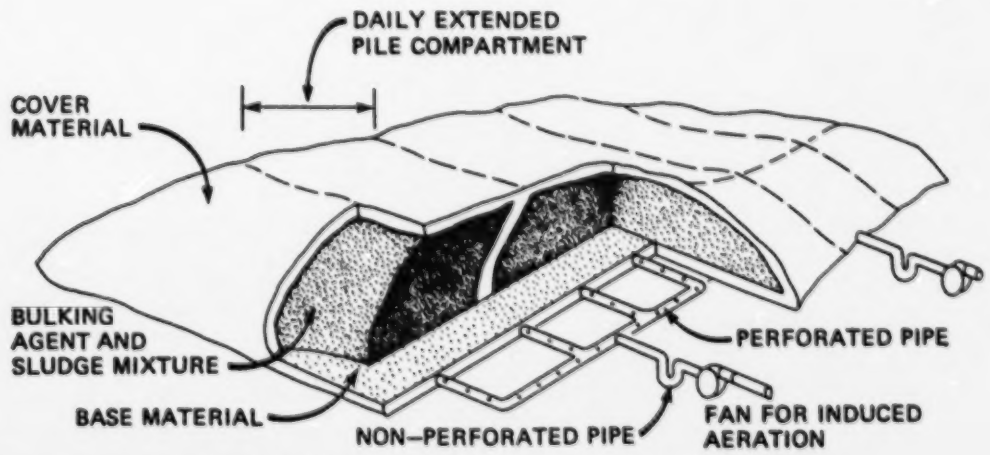

Figure 4—Extended aerated static pile composting method.

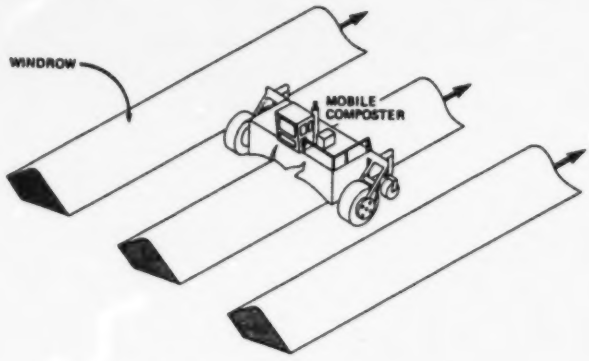

Figure 5—Conventional windrow composting method.

10-cm perforated pipe for an aerated drying step before screening. Constant aeration is applied during drying with a goal of 52% total solids. This can generally be met within 4 to 5 days, even under wet-weather conditions.

Curing operations at each of the static pile facilities studied depend on materials management requirements. A minimum of 30 days is provided at all facilities. Unscreened compost is cured at the Columbus and Hampton Roads facilities, whereas screened compost is cured at the Site 2 facility. An advantage of screened compost curing is that it requires less area than unscreened compost curing. Aerated curing is used at Columbus and Site 2, but not at Hampton Roads.

Screening. The screening operation assessment at the Hampton Roads, Site 2, and Columbus facilities demonstrates the need to define screening effectiveness, including expected variability, in aerated static pile applications. Under optimum conditions, wood chip recoveries based on unscreened compost volume can be 80 to 90%. However, this requires that unscreened compost total solids content be between 50 and 60%, dependent in part on screen size and design. If the upper limit is exceeded, losses from excessive dust generation will result, while failure to meet the lower limit inhibits separation of fines from wood chips and leads to wood chip contamination, reduced screening rates, and often mechanical problems with the screening equipment. Wood chip recoveries of 65 to 85% are more typical of sustained routine operation based on experience at the three static pile facilities.

For example, at the Site 2 facility, which uses fully enclosed screening equipment, 85 to 87% of the wood chips were consistently recovered during dry weather. However, under wet, cold weather conditions, screening problems occurred and efficiencies were less, even with effective moisture control in the unscreened compost. At the Hampton Roads facility, three replicate screening tests at an unscreened compost total solids content of 56% achieved an average wood chip recovery of 75%. By comparison, a review of facility records for 3 months of routine operation showed 42 to 93% recoveries, with an average of 64%. Unscreened compost total solids content for these months was between 46 and 79%.

CONVENTIONAL WINDROW OPERATIONS

The evaluation of conventional windrow composting was limited to operations at the 450-wet Mg/d Los Angeles facility. This facility was not extensively planned, evaluated and designed but, rather, evolved over the years and has been the source of extensive research projects that deal with the fundamentals of the windrow composting process.

Site features. A breakdown of areas used for various operations at the Los Angeles facility is presented in Table 4. Although total site area is about 20 ha, the principal areas currently used are the south composting area, and the bulking agent, equipment, and finished compost storage areas. Thus, the operating area for the Los Angeles facility is about 15 ha, or 0.03 ha/wet Mg·d. All operations are uncovered.

Sludge loadings. The Los Angeles facility processes dewatered, anaerobically digested sludge. Facility personnel established, by trial-and-error, that loadings greater than 450 wet Mg/d resulted in odor complaints; consequently, operation is now managed to meet this constraint. Total solids content of dewatered sludge received at the Los Angeles facility is typically 22 to 25%, with a volatile content of about 50%.

Premixing and windrow formation. A two-step preliminary mixing and windrow formation operation is used at the Los Angeles facility. Semi-trailers loaded with sludge and amendment are driven to the windrow pad where the contents are discharged such that two small windrows are formed side by side. Each small windrow is first mixed with a front-end loader and then the two are pushed into a single windrow, which is typically 1.2 to 1.5 m high and 4 m wide at the base. Because the preliminary front-end loader mixing has not been completely effective, installation of enclosed pugmill mixing stations are being considered. After preliminary mixing and windrow formation a 6 Mg/min mobile composter is used to fine-mix the windrow for active composting.

Active windrow composting. Active conventional windrow composting at the Los Angeles facility is performed during a 30- to 90-day period, dependent on ambient temperatures and drying rates. A typical operation consists of forming six 1.2- to 1.5-m by 4-m windrows (as described previously) during the first week, after which two large windrows, each about 2.1 m high and 7 m wide at the base, are formed from the six smaller windrows. The large windrows help maintain internal windrow temperatures, which are monitored to ensure that at least 55°C is maintained for 15 days. The large windrows are then torn down and finished compost is either delivered to a private company for distribution, or retained for recycle in the composting process. During the active composting period, a 6 Mg/min mobile composter mixes and aerates the 1.2- to 1.5-m by 4-m windrows, and a 10 Mg/min mobile composter mixes and aerates the large windrows. A turning frequency of three times per week provides adequate pathogen inactivation without affecting drying.

Experience at the Los Angeles composting facility has established that windrows should have an initial total solids content of at least 40% for composting to proceed satisfactorily. A total solids content of less than 40% results in a mixture of low porosity that inhibits oxygen transfer. The composting process is considered complete when windrow total solids content has increased to between 60 and 65%, and windrow volatile solids content has been reduced by about 5%.

AERATED WINDROW OPERATION

Because the Denver facility was developed for demonstration study, the operation assessment is based on an independent

Table 1—Key static pile site features.

Site feature	Hampton Roads facility	Site 2 facility	Columbus facility
Operating area, ha	2.5	16	15
Mixing			
Area, ha	0.12	0.45	0.16
Paved	Concrete	Concrete	Asphalt
Covered	Yes	Yes, enclosed two sides	Partially enclosed
Equipment	Front-end loaders with manure spreader or rototiller	Front-end loaders and mobile composter	Front-end loaders only
Bulking agent	Wood chips	Wood chips	Wood chips
Active composting			
Area, ha	0.45	1.01[a]	1.50
Paved	Concrete	Concrete	Concrete
Covered	No	Yes	No
Aeration piping	Laid in troughs in pad	Laid on pavement	Laid on pavement
Induced aeration	Positive and negative	Negative	Positive
Drying			
Area, ha	0.69	0.32[a]	—
Paved	Concrete	Concrete	—
Covered	No	Yes	—
Method	Spread and rototilled on open slabs	Restacking with induced aeration	—
Screening			
Area, ha	0.08	0.40	0.20
Paved	Concrete	Concrete	—
Covered	Yes	Fully enclosed	No
Equipment	Mobile screens	Fixed screens	Mobile screens
Curing			
Area, ha	—[b]	1.34[c]	1.86
Paved	No	Concrete	Concrete
Covered	No	No	No
Aerated	No	Yes	Yes
Bulking agent storage			
Area, ha	0.16	1.82	0.36
Paved	Concrete	Asphalt	Concrete
Covered	No	No	No
Unscreened compost storage			
Area, ha	0.65[d]	—	4.05
Paved	No	—	Concrete
Covered	No	—	No
Finished compost storage			
Area, ha	0.16	—[e]	0.28
Paved	Concrete	—[e]	Asphalt
Covered	No	—[e]	Partially enclosed
Runoff collection			
Ponds	No	Yes	Yes
Area, ha	—	4.05	0.36

[a] Prescreen drying area is one-half of original active composting pad.
[b] Included as part of unscreened compost storage area.
[c] A 6-month storage/curing capacity for screened compost is provided.
[d] Includes curing.
[e] Included as part of curing area.

analysis of demonstration study results. The aeration system at the Denver facility consists of blowers, a manifold arrangement, and aeration troughs that were formed as part of the composting pad. Windrows are formed over these troughs and are typically 70 m long with a triangular cross-section 4 m wide at the base and 1.2 to 1.5 m high. In some cases, a 7.5-kW blower supplies aeration by a trough to a single windrow, while in other cases, a 19-kW blower supplies multiple windrows. During the demonstration study, active composting was generally conducted for a 30-day period, although shorter and longer times were sometimes required. Windrows were turned with a 4.5-Mg/min mobile composter, two to three times per week.

The aerated windrow demonstration project was designed to investigate, in part, three key process factors: induced aeration rate and mode, covered versus uncovered operation, and amendment requirements. All variables that affect composting

Table 2—Actual and design sludge loadings for static pile facilities.

Item	Hampton Roads	Site 2	Columbus
Design estimates			
Sludge total solids, percent	20	22	20
Sludge loadings			
Average wet Mg/d	45[a]	360[b]	180[a]
Average dry Mg/d	9	80	36
Peak-to-average day	Not specified	1.5	1.5
Current operations			
Sludge total solids, %			
Average	17	17	17
Minimum	14	15	13
Sludge loadings per operating day			
Average wet Mg	57	326	154
Average dry Mg	10	56	26
Peak-to-average day	1.6 to 1.8	1.4 to 1.6	1.9
Sludge loadings, percent of design			
Wet Mg basis	126	90	85
Dry Mg basis	110	70	73

[a] Operating or calendar-day basis not defined.
[b] Design considers operating days, but does not specifically designate the loading per operating day.

could not be controlled rigorously during the demonstration project, and thus, mean values were calculated to provide a generic assessment of the aerated windrow process for the technology evaluation. Table 5 summarizes total solids and total volatile solids changes during covered and uncovered windrow composting at Denver, with and without induced aeration. The active windrow composting period varied from 29 to 43 days; the mean periods were between 30 and 33 days for the data sets presented.

Table 3 shows that induced aeration improved drying by about 2 to 3% based on mean moisture reduction. Note, however, that the initial total solids content of many windrows was less than 40%, and that mean volatile solids destruction was marginal except for the uncovered windrows which used induced aeration. Mean moisture reductions presented in Table 3 were similar for both covered and uncovered windrows, an indication that covering the windrows did not enhance drying. Additionally, in many cases maximum temperatures for uncovered windrows were greater than 55°C for a longer duration than for covered windrows. The reason for this was not evident from this technology evaluation.

The effect of amendment use on aerated windrow composting at the Denver facility was assessed based on an analysis of demonstration study data from uncovered windrows that were formed with either recycled compost alone, or in conjunction with an external amendment such as wood chips or sawdust. Eighteen piles that used only recycled compost as an amendment yielded mean initial and final total solids of about 40 and 52%, respectively, with corresponding mean volatile solids of 54 and 51%. Eleven piles that incorporated other amendments with the recycled compost yielded mean initial and final total solids of 40 and 57%, respectively, with corresponding mean volatile solids of 59 and 58%. Although mean volatile solids destruction for those windrows that incorporated an external amendment was lower than for those that did not, drying was greater by about 5% for the former. Thus, the use of external amendment had a beneficial effect on drying during aerated windrow composting.

PERFORMANCE COMPARISON

Finished compost is sold to local users at all of the facilities investigated, except Denver. Demand varies with season and thus materials management procedures for low-use periods are necessary. Long-term finished compost production at three of the facilities studied is summarized in Table 6. Representative values of finished compost total solids content for the Hampton Roads, Site 2, and Los Angeles facilities are 52, 51, and 60%, respectively, and corresponding bulk densities are 550, 650 to 900, and 750 kg/m^3. Los Angeles facility data are based on recycling finished compost without external amendments.

Finished compost production for the static pile facility (Site 2) which processes raw, limed sludge is greater than that for the static pile facility (Hampton Roads) that processes anaerobically digested sludge. Dewatered sludge and finished compost total solids are similar for each facility; however, the former is designed to process 360 wet Mg/d, while the latter processes about 45 wet Mg/d. Finished compost bulk density for the facility that processes raw, limed sludge is greater than that for the facility that processes anaerobically digested sludge.

Finished compost production for the aerated static pile (Hampton Roads) and conventional windrow (Los Angeles) facilities that process anaerobically digested sludge are similar. The conventional windrow system processes about 450 wet Mg/d of sludge, while the static pile facility treats 45 wet Mg/d. Dewatered sludge total solids content at the conventional windrow facility (23%) is higher than that at the static pile facility (17%).

Although the long-term finished compost production figures presented in Table 6 are useful for general comparisons, operational variables affect actual day-to-day output, as illustrated by data from the Columbus facility. At this facility, finished compost production is much lower than the values in Table 6—currently about 0.2 dry Mg/dry Mg sludge (0.1 m^3/wet Mg). Finished compost bulk density is about 650 to 700 kg/m^3, and total solids content is about 52%. The low finished compost production rate is the result of wet-weather screening problems that require long storage periods for unscreened compost. Consequently, this rate does not represent performance that could be achieved routinely with efficient screening.

ODOR CONSIDERATIONS

The earthy smell of stabilized compost was often detected in the immediate vicinity of all of the composting facilities. Key design and operational features that minimize generation or release of objectionable odors are as follows:

Table 3—Pile construction and aeration features.

Item	Hampton Roads	Site 2	Columbus
Pile dimensions, daily compartment, m			
Length	34	34	60
Width	2.5–3.0	6	3.5
Height	4.0	3.5	3.5–4.0
Base material			
Depth, cm	30–45	30	30
Central pile	New wood chips	New wood chips	New wood chips
Toes (distance from pile end)	Unscreened compost (3.0 m)	Unscreened compost (3.5 m)	Same as central area
Cover material			
Depth, cm	45 (summer)	45	45
	60 (winter)	—	—
Type	Unscreened compost	Screened or unscreened compost	Unscreened compost
Special cover	10–15 cm of screened compost on face of toes	—	—
Aeration piping			
Placement	Laid in trough cast into composting pad	Laid directly on paved composting pad	Laid directly on paved composting pad
Type	Rigid	Flexible	Flexible
Material	PVC	Plastic	Polyethylene
Diameter, cm	15	15	13
Pipe laterals per daily compartment	1	4	2
Lateral length unperforated, m	7	4.5	4–9
Lateral length perforated, m	27	26.5	56
Perforation spacing	Uniform	Variable	Uniform
Perforation area, cm^2/m	18.71	8.78–90.59	84.67
Aeration blowers[a]			
Total number	8	42	40
Capacity, each, kW	2.2	11	0.75
Capacity, total, kW	17.6	462	30
Unit capacity, kW per wet Mg/d[b]	0.39	1.28	0.17
Process control			
Aeration rate, $m^3/h \cdot$ day Mg	31–87	110–187	—
Aeration rate control procedure	Manual	Automatic	Manual
Temperature monitoring technique	Probes left in pile; read daily	Probes left in pile; connected to blower controls	Periodic temperature probe readings
Number of points	6	5	Random
Oxygen monitoring technique	Monitoring tubes, daily readings	Monitoring tubes, daily readings	Not monitored
Number of points	3	3	—

[a] Active composting only.
[b] Based on design loadings.

• Trucks used to haul dewatered sludge, particularly raw sludge, should be covered and cleaned frequently.

• Dewatered sludge deliveries should be scheduled so that mixing and other operations can be performed without sludge accumulation for long periods. This is particularly important with raw sludge and in hot weather.

• An initial mix moisture content of 60% or less (total solids ≥40 percent) is a key process design criterion for effective performance, including odor control. Enclosed mixing with exhaust gas scrubbing can effectively control odor in some situations.

• A uniformly mixed and sufficiently porous material is important for odor control during composting. Clumps of unmixed sludge can lead to anaerobic, and thus odorous, conditions, as well as incomplete stabilization and pathogen inactivation. Construction of daily static pile compartments, with cover material, is also important.

• Positive aeration during active static pile composting can minimize odor potential because the pile cover material acts as an odor scrubber. Negative aeration requires the use of a separate

Table 4—Areas used for various operations at the Los Angeles facility.

Site feature	Approximate area, ha
South composting field	10
North composting field	4
Bulking agent storage	2.4
Finished compost storage	2.2
Equipment storage	0.2
Research area	1.2
Total site	**20.0**

Table 5—Generic assessment of Denver study results.

Windrow composting mode	Amendments	Composting parameter, %	Stage of compost cycle[a]	Covered windrows Mean	Covered windrows Range	Uncovered windrows Mean	Uncovered windrows Range
No induced aeration with turning every other day[b]	Recycled compost with various amendments	Total solids	Initial	31.0	26.8–37.4	30.8	26.8–37.4
			Final	37.8	29.6–47.9	38.2	33.8–48.4
		Total volatile solids	Initial	61.3	45.0–70.8	61.3	45.0–70.8
			Final	61.0	48.7–78.2	60.0	47.8–76.4
		Moisture reduction	—	6.8	—	7.4	—
		Volatile solids reduction	—	0.3	—	1.3	—
Induced aeration with turning every third day	Recycled compost with various amendments[c]	Total solids	Initial	40.1	37.5–42.7	36.1	32.6–38.7
			Final	50.2	45.1–59.4	45.4	41–55.8
		Total volatile solids	Initial	59.9	58.7–61.8	63.9	60.5–65.9
			Final	61.1	52.5–72.6	58.0	53.7–62.0
		Moisture reduction	—	10.1	—	9.3	—
		Volatile solids reduction	—	—	—	5.9	—

[a] Initial—sample of windrow material obtained on day windrow was constructed. Final—sample of windrow material obtained on day windrow was torn down.
[b] Six determinations.
[c] Nine to 11 determinations.

exhaust scrubber system such as a finished compost filter pile. Regardless of the aeration mode, control of aeration rate, oxygen content, and temperature is critical for effective odor control and proper composting.

- Experience at the Los Angeles conventional windrow facility demonstrated, by trial and error, the need to limit the quantity of sludge processed to minimize odor complaints. Personnel at this location have performed studies that indicate 83% of the odor emissions from the windrow operation are the result of ambient surface emissions and 17% are the result of windrow turnings. Additionally, it was found that the intensity of ambient surface emissions decrease as the composting period progresses and that emissions are greatest immediately after windrow turning.
- Teardown of static piles or windrows can be managed to minimize release of odors. At one static pile facility, piles are not torn down during wet weather or in early morning hours when air inversions may generate odor. At another, high-rate aeration for 24 to 48 hours prior to teardown, which lowers pile temperature to ambient, is used to control odor release.
- An effective leachate, condensate, and runoff collection and disposal system will minimize odor. Proper site drainage is required to prevent ponding, which can generate odor.
- Effective housekeeping procedures such as washing equipment and flushing or sweeping working areas such as mixing pads can also reduce odor.

Table 6—Long-term finished compost production.

Facility	m^3 compost/wet Mg sludge	Dry Mg compost/dry Mg sludge
Hampton Roads	0.4–0.6	0.7–0.9
Site 2	0.8	1.6–2.2
Los Angeles	0.3–0.4	0.6–0.8

ECONOMIC EVALUATION

Capital expenditures. The Columbus, Hampton Roads, and Site 2 static pile facilities were built in 1980, 1981, and 1983, respectively. Since initial construction, additional capital expenditures have been required at each installation to improve or modify operation. Actual capital costs for the three static pile facilities are summarized by year in Table 7. The Los Angeles conventional windrow facility has evolved gradually since composting activities were initiated in the early 1970s, and thus comparable capital costs are not available. Costs adjusted to 1985 vary because features at each facility vary (Table 1).

Operating costs. Annual operation and maintenance (O&M) costs in 1985 dollars for the three static pile facilities and the Los Angeles conventional windrow facility are presented in Table 8. Costs shown were calculated from actual costs based on mid-year, U. S.-average Consumer Price Indexes (CPIs) for urban wage earners and clerical workers. The table shows that on-site labor costs, including fringe benefits, comprise about 24 to 50% of the annual static pile O&M costs, excluding sludge transport. Combined costs for on-site labor, new wood chip purchase, and aeration piping account for 50 to 80% of the annual O&M costs, excluding sludge transport. Administrative costs vary because administrative charges, for example, fuel costs, are allocated in different ways at each facility.

Table 7—Capital costs for static pile facilities.

Facility	Year	Capital cost, thousand dollars[a] Actual	Adjusted to 1985[b]
Hampton Roads	1981	1 068[c]	1 260
	1982	143	157
	1983	1 091	1 124
	1984	30	24
	Total	—	2 565
Columbus	1980	1 268	1 648
	1982	1 486	1 635
	1983	3 230	3 327
	Total	—	6 610
Site 2	1983	16 703[d]	17 204
	1984	493	404
	Total	—	17 608

[a] Cost of engineering, administration, interest during construction, and land purchase are not included.

[b] Adjusted based on ENR 20-Cities Construction Cost Indexes for mid-year 1980 through 1985.

[c] Excludes $255 000 for purchase of sludge transport trucks.

[d] Excludes land cost and cost for on-site, mobile equipment.

Utilities and administrative costs for the Los Angeles facility were not readily available during the technology evaluation and are not included. Labor cost is the major O&M cost item (63%); fuel and equipment maintenance are 15 and 16%, respectively. Although the Los Angeles facility uses external amendments as well as recycled compost for conventional windrow composting, there is no purchase cost for these amendments. Unit O&M costs in 1985 dollars, excluding sludge transport, for the Hampton Roads, Columbus, and Site 2 facilities are about $35, $28, and $40/wet Mg, respectively, or $206, $165, and $235/dry Mg. Annual sludge transport costs were available for the Hampton Roads and Site 2 facilities. When these costs are included, unit O&M costs in 1985 dollars increase to about $44/wet Mg at the Hampton Roads facility and $43/wet Mg at the Site 2 facility.

Unit O&M costs for the Los Angeles conventional windrow facility are not directly comparable to those for the static pile facilities because of different facility capacities, and because comparable O&M costs for all cost categories presented in Table 8 were not available. However, based on the costs that were available, the unit O&M cost in 1985 dollars at the Los Angeles facility is about $8/wet Mg, or $34/dry Mg.

Compost sales revenue. Annual and unit O&M costs presented in the previous section do not reflect revenues generated from the sale of finished compost at each facility. Table 9 summarizes annual sales revenues in 1985 dollars, based on the actual revenues shown. Revenues received are approximately $2.75, $0.65, $1.55, and $1.10/wet Mg at the Hampton Roads, Columbus, Site 2, and Los Angeles facilities, respectively.

Net O&M costs after compost sale in 1985 dollars at Hampton Roads, Columbus, and Site 2 are $32, $26, and $38/wet Mg, excluding sludge transport. At Hampton Roads, the quantity of compost sold, 4280 m^3, represents about 60 to 70% of the annual finished compost production. At Site 2, the annual quantity of compost currently sold is about 25 230 m^3 or 34% of annual production. Corresponding figures for Columbus were not available. All three facilities have programs to increase compost sales in the future. At the Los Angeles facility, compost is sold by contract to a private company for distribution, reducing the annual O&M cost to $7/wet Mg.

CONCLUSIONS

The technology evaluation was performed to assess a broad range of municipal sludge composting activities related to design, operation, performance, and economics and the findings are not intended to be used for design purposes. Furthermore, the aerated static pile and windrow facilities varied in size, type of sludge composted, geographic location, climatic conditions, and such site-specific factors as surrounding land use characteristics, mar-

Table 8—Annual O&M costs, adjusted to 1985 dollars.

Cost category	O&M Hampton Roads	Columbus	Site 2	Los Angeles
On-site O&M				
Labor, including fringe benefits	195.0	497.5	828.5	624.0
Bulking agent and aeration piping	179.0	210.0	803.0[b]	—
External amendments	—	—	—	0.0[c]
Utilities	3.0	35.5	191.0	—
Fuel	22.5	—[d]	—[e]	148.0
Equipment maintenance	49.5	139.0	—[e]	156.0
Laboratory and other expenses	2.5[f]	83.0[f]	109.0[g]	60.0
Subtotal, on-site O&M	451.5	965.0	1931.5	988.0
Administration	15.5[h]	82.5	1551.0[i]	—[j]
Subtotal, excluding sludge transport	467.0	1047.5	3482.5	—
Long-haul sludge transport	107.0[k]	—[l]	275.0[i]	—[m]
Total O&M	574.0	—	3757.5	—

[a] In thousand dollars, rounded to nearest $500.

[b] Most of this cost is for bulking agent (new wood chips, which are typically 0 to 40 percent of total bulking agent volume requirements). Other services include costs for asphalt repair, janitorial services, protective clothing, and related expenses.

[c] Amendments are used in the windrow operation but they are obtained at no cost.

[d] Not available.

[e] Fuel and maintenance cost is included in cost for administration.

[f] Analytical work is performed at the associated treatment plant. Cost is not included.

[g] Includes rental of a standby generator ($67 000).

[h] Labor only, including a part-time agronomist for compost marketing.

[i] Includes cost of fuel and equipment, per footnote "e."

[j] Management and administration is provided by personnel at the Joint Water Pollution Control Plant.

[k] Labor and fuel only. Maintenance cost not available.

[l] Provided by contractor. Cost not available for Columbus facility.

[m] Compost facility is located adjacent to the treatment plant so there is no long-haul sludge transport cost.

Table 9—Annual revenue from compost sale.

Facility	Actual revenue		Adjusted revenue, 1985 dollars[a]	Compost quantity sold, m^3
	Year	Dollars		
Hampton Roads	1984	35 124	36 972	4 280
Columbus	1983	23 200[b]	25 160	—
Site 2	1984	129 000[c]	135 783	25 230[c]
Los Angeles	1985[d]	148 500[d]	148 500	—

[a] Based on CPIs.
[b] Actual revenue presented is projected from a value of $5800 for the last 3 months of 1983 when the marketing program was initiated.
[c] Estimated from actual values for the 20-month period from April 1983 to November 1984.
[d] Estimated from information for the last quarter of 1984 and the first quarter of 1985.

ket potential for finished compost, type of equipment, and operating procedures applied. Facilities which use in-vessel, mechanical composting processes were not investigated. Considering these constraints, the following conclusions can be drawn.

- Unit operating areas vary widely dependent on site-specific considerations and requirements. Based on the 45- to 450-wet Mg/d facilities studied, unit operating areas of about 0.03 to 0.08 ha/wet Mg · d are required.
- Moisture control, combined with effective mixing, during day-to-day operation was the single most important factor for effective composting. Moisture must be controlled for effective stabilization, pathogen inactivation, odor control, and finished compost quality control, whether it is in incoming dewatered sludge, the bulking agent, or amendment, whether it is added by inclement weather, or whether it is generated as a byproduct of the composting process. An initial mix moisture content of 60% or less (total solids ≥40 percent) was a key criterion for effective performance regardless of the composting technology used.
- Flexibility to respond to variable sludge loadings, weather conditions, and day-to-day problems was also an important operating requirement. Lower-than-anticipated dewatered sludge total solids content affected operations at all of the facilities investigated, and various methods have been and are being applied to mitigate problems created by this situation.
- Under optimum conditions, wood chip recoveries of 80 to 90%, based on unscreened compost volume, can be achieved during screening. However, recoveries of 65 to 85% are more typical of routine operation.
- The integration of treatment plant and composting operations is important for effective composting. This was accomplished by timing sludge deliveries, coordinating plant operations such as dewatering with composting constraints, and providing sludge storage.
- Based on experience at one conventional windrow facility, preliminary mixing with front-end loaders before windrow formation has not been completely effective; therefore, pugmill mixing is being considered as an alternative. The use of large windrows, typically 2.1 m high and 7 m wide at the base, effectively maintains internal temperatures and minimizes area required during active composting.
- Based on an independent analysis of demonstration study results from one aerated windrow facility, induced aeration improved drying by about 2 to 3% over conventional windrowing. Use of external amendments in conjunction with recycled compost was also found to aid drying, but covering windrows did not help.
- Sustained finished compost production was equivalent to about 0.6 to 2.2 dry Mg/dry Mg sludge processed, or 0.3 to 0.8 m^3/wet Mg. Finished compost production was affected by the type of sludge processed, but not the composting technology.
- The chief environmental problem at the facilities studied was odor generation and its resulting off-site impact.
- Capital and annual O&M costs are site-specific. However, based on operations at the three static pile facilities, O&M costs in 1985 dollars for this technology were about $28 to $40/wet Mg, or $165 to $235/dry Mg. These costs do not include amortized capital, dewatering, or sludge transport costs. Comparative unit O&M costs for windrow technologies were not readily available.
- On-site labor, wood chip purchase, and aeration piping replacement accounted for 50 to 80% of the annual O&M cost at the static pile facilities.
- Revenues generated from the sale of finished compost varied from $0.65 to $2.75/wet Mg, in 1985 dollars, based on current marketing programs at the facilities.

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